DIRECT SEARCHES FOR DARK MATTER PARTICLES: WIMPS AND AXIONS

IGOR G. IRASTORZA
CEA, Centre d'Etudes Nucléaires de Saclay,
DSM/DAPNIA, 91191 Gif-sur-Yvette Cedex, France
E-mail: Igor.Irastorza@cern.ch

WIMPs and axions are the two best motivated candidates to compose the Dark Matter of the Universe. An important number of experimental groups are developing and using different techniques for their direct detection. An updated review of current searches is done, emphasizing latest results.

1 Introduction

Since first suggested by Zwicky in the 1930s, the existence of an invisible and unconventional matter as a dominant part of our Universe has been supported by an ever increasing body of observational data. The latest precision cosmology measurements [1] further constrain the geometry of the Universe to be flat ($\Omega \sim 1 \pm 0.04$), and its composition (to the level of a few %) to be mostly dark energy ($\Omega_\Lambda \sim 73\%$) and non-baryonic dark matter ($\Omega_{NB} \sim 23\%$), leaving less than $\sim 4\%$ for ordinary baryonic matter. Dark energy is a theoretical concept related to Einstein's cosmological constant, the nature of which is essentially unknown. Dark matter, on the contrary, could be composed by elementary particles with relatively known properties, and which could be searched for by a variety of means. These particles must have mass, be electrically neutral and interact very weakly with the rest of matter. They must provide a way of being copiously produced in the early stages of the Universe life, so they fill the above-mentioned $\sim$23% of the Universe contents. Neutrinos are the only standard particles fitting in that scheme, but the hypothesis of neutrinos being the sole component of dark matter fails to reproduce part of the cosmological observations, in particular the current structure of the universe. The dark matter problem is therefore solved only by going into models beyond the standard model of elementary particles, among which two generic categories emerge as the best motivated for the task: WIMPs and axions.

WIMP is a generic denomination for any Weakly Interacting Massive Particle. A typical example of WIMP is the lightest supersymmetric particle (LSP) of SUSY extensions of the standard model, usually the neutralino. They would have been thermally produced after the Big Bang, cooled down and then frozen out of equilibrium providing a relic density[2,3]. The interesting

mass window for the WIMPs spans from a few GeV up to the $\sim$ TeV scale, but can be further constrained for specific models and considerations.

Axions, on the contrary, are light pseudoscalar particles that are introduced in extensions of the Standard Model including the Peccei-Quinn symmetry as a solution to the strong CP problem[4]. This symmetry is spontaneously broken at some unknown scale f_a, and the axion is the associated pseudo-Goldstone boson [5,6]. The axion framework provides several ways for them to be produced copiously in the early stages of the Universe, which makes it a leading candidate to also solve the dark matter problem[7,8].

The hypothesis of axions or WIMPS composing partially or totally the missing matter of the Universe is specially appealing because it comes as an additional bonus to what these particles were originally thought for, i.e. they are not designed to solve the dark matter problem, but they may solve it. In addition, the existence of WIMPs or axions could be at reach of the sensitivity of current or near future experiments, and this has triggered a very important experimental activity in the last years. In the following pages a review is given of the current experimental efforts to detect these particles by direct means, i.e. aiming at their direct interaction with terrestrial detectors. Indirect methods, like those looking for their decay products in astronomical or cosmic rays observations may also put constraints on the properties of these particles[9,10], although they suffer from extra degrees of uncertainties, like the phenomenology driving the accumulation of dark matter particles in astrophysical bodies and their decay into other particles, and they are left out of the scope of the present review.

2 WIMP searches

If WIMPs compose the missing matter of the universe, and are present at galactic scales to explain the observed rotation curves of the galaxies, the space at Earth location is supposed to be permeated by a flux of these particles characterized by a density and velocity distribution that depend on the details of the galactic halo model[11,12,13]. A common estimate [14] (although probably not the best one) gives a local WIMP density of 0.3 GeV/cm^3 and a maxwellian velocity distribution of width $v_{rms} \simeq 270$ km/s, truncated by the galactic escape velocity $v_{esc} \simeq 650$ km/s and shifted by the relative motion of the solar system through the galactic halo $v_0 = 230$ km/s.

The direct detection of WIMPs relies on measuring the nuclear recoil produced by their elastic scattering off target nuclei in terrestrial –usually underground– detectors[17]. Due to the weakness of the interaction, the ex-

pected signal rates are very low ($1-10^{-5}$ c/kg/day). In addition, the kinematics of the reaction tells us that the energy transferred to the recoiling nuclei is also small (keV range), which in ionization and scintillation detectors may be further quenched by the fact that only a fraction of the recoil energy goes to ionization. These generic properties determine the experimental strategies needed. In general, what makes these searches uniquely challenging is the combination of the following requirements: thresholds as low as possible, and at least in the keV range; ultra low backgrounds, which implies the application of techniques of radiopurity, shielding and event discrimination; target masses as large as possible; and a high control on the stability of operation over long times, as usually large exposures are needed.

Even if these strategies are thoroughly pursued, one extra important consideration is to be noted. The small WIMP signal falls in the low-energy region of the spectrum, where the radioactive and environmental backgrounds accumulate at much faster rate and with similar spectral shape. That makes WIMP signal and background practically indistinguishable by looking at their spectral features. If a clear positive detection is aimed for, then more sophisticated discrimination techniques and specially more WIMP-specific signatures are needed. Several positive WIMP signatures have been proposed, although all of them pose additional experimental challenges. The first one is the *annual modulation*[15] of the WIMP signal, reflecting the periodical change of relative WIMP velocity due to the motion of the Earth around the Sun. The variation is only of a few % over the total WIMP signal, so even larger target masses are needed[16] to be sensitive to it. This signal may identify a WIMP in the data, provided a very good control of systematic effects is available, as it is not difficult to imagine annual cycles in sources of background. A second WIMP signature is the *A-dependence signature*[17], based on the fact that WIMPs interact differently (in rate as well as in spectral shape) with different target nuclei. This signature should be within reach of set-ups composed by sets of detectors of different target materials, although the technique must face the very important question of how to assure the background conditions of all detectors are the same. Finally, the *directionality signature*[18] is based on the possibility of measuring the nuclear recoil direction, which in galactic coordinates would be unmistakably distinguished from any terrestrial background. This option supposes an important experimental challenge and it is reserved to gaseous detectors, where the track left by a nuclear recoil, although small, may be measurable.

Most of the past and current experiments having given the most competitive results are not sensitive to any of these positive WIMP signatures,

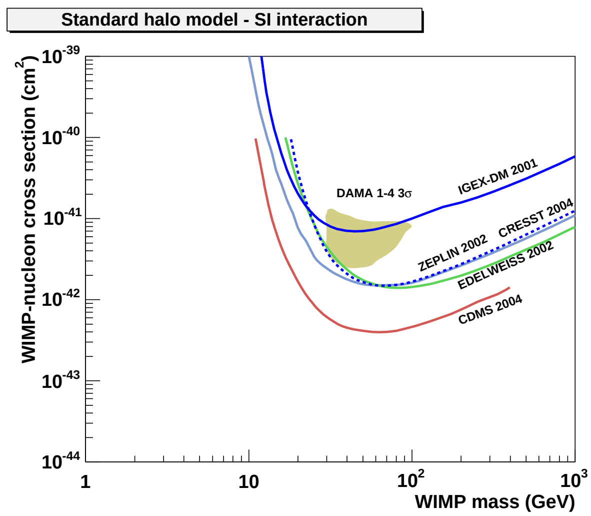

Figure 1. Exclusion plots of the IGEX-DM, ZEPLIN-I, CRESST, EDELWEISS and CDMS experiments, as well as the positive region of the DAMA experiment (only first 4 annual cycles). Standard assumptions for the halo model and a pure spin-independent WIMP-nucleon interaction have been considered. See text for more details.

and their reported results are usually exclusion plots in the (σ_N, M) plane, obtained by comparing the total spectra measured directly with the nuclear recoil spectrum expected for a WIMP (where σ_N is WIMP-nucleon cross section and M the the WIMP mass). For the sake of comparison between experiments, these exclusion plots, like the ones in fig. 1, are usually calculated assuming the standard properties for the halo model previously mentioned, and a spin independent WIMP-nucleus interaction. For a discussion on how other halo models or the inclusion of spin-dependent interactions affects these exclusion plots see [11,12,13]. As will be discussed in the following pages, the DAMA experiment claims the detection of an annual modulation in their data, although the interpretation as a WIMP signal is controversial. Recent progress in the experimental techniques promises that experiments in the near future will have wider access to the three positive signatures previously mentioned in case a WIMP is detected.

In the following a review of the current status of the experimental WIMP searches is done, focussing on the latest and most important results and developments. For an exhaustive and historical listing of experiments we refer to [19,20,21].

2.1 Ionization detectors

Ionization germanium detectors represent the conventional approach of a well-known technology, where radiopurity, background reduction and shielding techniques have been optimized extraordinarily during the last two decades, in the context of double beta decay searches. The result released by the IGEX collaboration in 2001[22], shown in fig. 1 exemplifies the state-of-the-art in raw background reduction techniques. The result was obtained with a setup in the Canfranc Underground Laboratory composed by an ultrapure germanium detector of 2.1 kg, surrounded by a shielding of ultrapure components, including an innermost core of 2.5 tons of 2000-year-old archaeological lead forming a 60 cm side cube, flushed with clean N_2 to remove radon and followed by an extra 20 cm of radiopure lead, a cadmium sheet, muon vetos and 40 cm of neutron moderator. The achieved threshold was 4 keV, and the background level was 0.21 c/keV/kg/d between 4-10 keV (0.10 in 10-20 keV, 0.04 in 20-40 keV), the lowest raw background level achieved up-to-date in this energy range.

Improved results using pure ionization detectors requires the important challenge of further refining the radiopurity and shielding techniques. The GEDEON[21] project proposes the conservative approach of following the same path of the successful IGEX technology, extended in mass, and further optimized from the point of view of radiocleanness. More exotic ideas exist, like the one proposed within the GENIUS[23] project, of submerging the germanium crystals in liquid nitrogen, which may act as a very pure shielding. GENIUS-TF[24] is currently testing the concept. The GERDA[25] project, a high mass germanium experiment, proposed for double beta decay, has also joined the quest for WIMP searches.

2.2 Scintillation detectors

Scintillation detectors have been extensively used for WIMP detection, specially because they are the technique which provided the easiest way to large target masses. It was in fact a first setup of NaI scintillators which first looked for the annual modulation signature[26]. With no so good prospects concerning low background capabilities as germanium detectors, scintillation may however provide a way –although limited– to discriminate between nuclear recoils and electron recoils, due to their slightly different scintillation decay times.

Currently, the DAMA group gathers the expectation of the field with its claim of observation of an annual modulation signal of unexplained origin and perfectly compatible with a WIMP of ~ 52 GeV and $\sim 7.2 \times 10^{-6}$ pb (and standard assumptions for the halo model). The DAMA experiment in the

Gran Sasso Laboratory, now completed [27], operated 9 radiopure NaI crystals of 9.7 kg each, viewed by two PMT in coincidence gathering 107731 kg day of statistics and obtaining evidence for the modulation along 7 annual cycles. The DAMA positive signal has been ruled out by other experiments in the standard scenario represented by the exclusion plots of fig. 1. However, in view of the important uncertainties in the underlying theoretical frameworks and in the galactic halo models, it is unclear, and a matter of hot discussion, whether all results are compatible once all uncertainties are taken into account. It seems that one can always concentrate on a specific theoretical framework that allows to accommodate both DAMA positive result and the other exclusion plots[27]. An additional result using the same target seems to be needed to solve the controversy. The same DAMA team is already running an enlarged set-up of $\sim$ 250 kg of NaI (LIBRA[28]) and will soon deliver the first set of data. An independent result will come from the ANAIS experiment[29], currently in the way of instrumenting its $\sim$ 100 kg of NaI in the Canfranc Underground Laboratory.

Other scintillating materials have been used in the past. Worth to be noted is the recent result obtained by the KIMS group, using CsI crystals[30]. This material offers a higher potential of discrimination between nuclear and electron recoils when compared with NaI, due to the enhanced difference between the scintillation pulse time pattern.

Experiments using liquid noble gases, especially Xenon, should be classified half way between ionization and scintillation. The scintillation mechanism in noble gases is very different than in the previous cases, and allows for an improved discrimination capability by exploiting the different time patterns of the scintillation pulses of nuclear and electron recoils or, more efficiently, by using the ratio charge/light when operating in hybrid mode. This second possibility is available in two-phase prototypes, where an electric field is applied to prevent recombination and to drift the electrons to the gaseous phase where they are detected (via the secondary luminescence).

Several groups are developing and using noble liquid detectors for WIMP searches. They have proven that this technique provides good prospects of radiopurity and background discrimination and relatively easy scaling-up. DAMA/Xe[31,32] is among the pioneers of the technique, originally motivated for double beta decay searches. The Xenon program carried out by the ZEPLIN collaboration in the Boulby Mine Laboratory has produced several prototypes. The ZEPLIN-I[33] prototype, using 6 kg of Xenon in pure scintillation mode, has provided a very competitive result shown in fig. 1. Current effort focuses on the second phase of the experiment, ZEPLIN-II,

that will operate in the two-phase mode. In additon to ZEPLIN, the groups XENON[34] and X-MASS[35] work towards the design and construction of 100 kg prototypes with position sensitivity. The key question beneath this is the self-shielding concept, consisting in performing fiducial cuts of the detector to achieve the maximum signal-to-background ratio, exploiting the fact that external background will interact primarily in the outer parts of the detector volume. For future generation, larger scale detectors this concept may become very important, as discussed later. Let us mention finally that large TPCs of liquid Argon have been also proposed, like for example the WARP[36] collaboration which profits from the experience of the ICARUS experiment in those techniques.

2.3 Cryogenic detectors

Nuclear recoils can also be detected through the heat (phonons) created in the detector by the recoiling nucleus. This signal is detectable in calorimeters operating at cryogenic temperatures, to which a suitable thermometer is attached. At those temperatures, the released heat produces a temperature raise that can be measurable.

The main advantage of this technique is that most of the energy of the interaction is visible and therefore no quenching factor must be applied. Besides, the phonon signal potentially provides the best energy resolution and thresholds. On the other hand, however, the operation of cryogenic detectors is a relatively complex technique facing many challenges when going for larger exposure times and masses. For the same reason, radiopurity techniques are also more difficult to apply.

A reference point in pure cryogenics detectors is the pioneering work of the Milano group, now leading the CUORE/CUORICINO experiment[37,38] in the Gran Sasso Laboratory. The CUORE project, designed to search for the neutrinoless double beta decay of ^{130}Te, intends the construction of an array of 988 TeO_2 cryogenic crystals, summing up $\sim$ 750 kg of bolometric mass. A first step of the project, CUORICINO, is already in operation and involves 62 ($\sim$40.7 kg) crystals, by far the largest cryogenic mass in operation underground. Although background levels are still too high to provide competitive limits in WIMP detection, important progress is being made and CUORE may have very good sensitivity to WIMP annual modulation[39].

However, cryogenic detectors have taken the lead on WIMP searches because of the possibility of operating in hybrid mode. Due to the large choice of target materials available to the cryogenic techniques, and when the material in question is a semiconductor or a scintillator, the detector could in principle

be operated in hybrid mode, measuring simultaneously the heat and charge or the heat and light respectively. This strategy has proven to be the most competitive and efficient in discriminating nuclear recoils from electron recoils. In fact, cryogenic ionization experiments, like CDMS[40] in the Soudan Underground Laboratory and EDELWEISS[41] in the Modane Underground Laboratory, have provided the best WIMPs exclusion plots up-to-date[a], shown in figure 1. Both experiments presently operate prototypes at $\sim$1 kg scale, and although their raw backgrounds are relatively high with respect with pure ionization experiments, they reject more than $\sim$99.9% of the electron recoils (by comparing heat and charge signals), reducing the background to only a few counts, compatible with the expected neutron background or the misidentification event rate). Both groups currently work toward increasing the mass of their set-ups and therefore the available exposure.

Although currently less competitive than heat and charge, the simultaneous measurement of heat and light is recently presenting very interesting prospects. The ROSEBUD group first applied it underground[43] and recently the CRESST collaboration has presented a very competitive exclusion plot obtained with two 300 g $CaWO_4$ prototypes[44] (dashed line in fig. 1). A very relevant feature of this result is that tungsten recoils can be distinguished -with some efficiency- from O or Ca recoils by virtue of their different ratio heat/light. This improves substantially the sensitivity of the experiment, as neutrons are expected to interact more with lighter nuclei, unlike WIMPs. In addition, recent scintillation studies [45] have shown that a large variety of scintillating crystals are available. This opens the way to use sets of different crystals operating in this mode to look for the A-dependence WIMP signature. While the use of this signal in conventional detectors suffers from large uncontrolled systematics derived from the fact that one cannot assure the background to be the same for different crystals, light/heat hybrid detectors, sensitive only to neutrons, may overcome this difficulty. In this line, the ROSEBUD collaboration has successfully operated underground a set of 3 different bolometers in the same setup [46], sharing similar external background conditions.

2.4 New approaches and strategies for the future

Some techniques that fall out of the above classification have been proposed and some of them are being developed with some degree of success. They

[a] Very recently the CDMS collaboration has presented new preliminary results[42] that further improve the exclusion plot shown in fig.1

intent to solve some of the problems of the conventional previous techniques in new, original ways, to find identificative WIMP signatures or to explore possibilities less favoured by the most standard theoretical scenarios (like, for example, cases where the WIMP interacts primarily via spin-dependent cross sections). Without entering into details, worth to mention are the superheated droplets detectors, like SIMPLE[47], PICASSO[48], or detectors based on superfluid He^3, like MACHe3[49]. New ideas appear continuously, for example the spherical TPC concept[50,51], proposed in the context of neutrino physics, and which applicability to WIMP detection is under study.

An important category are the techniques aiming at the detection of the nuclear recoil direction. As mentioned before, such signal would suppose a definitive positive signature of a WIMP and would in addition give information about how they are distributed in the halo. While being an important technical challenge this measurement might be performed in gaseous detectors, where nuclei of $\sim 10 - 100$ keV could leave tracks in the mm–cm range (depending on the pressure and nature of the gas). The DRIFT[52] experiment is proving the technique of low pressure negative ion TPC[53]. Low pressure (40 Torr) makes the tracks to be relatively long (few cm), and the addition of electronegative gas (CS_2) makes the electrons to be captured, so the negative ions drift to the avalanche region (a multiwire proportional chamber) with much smaller diffusion and no magnetic field is needed. A first prototype DRIFT-I has already worked successfully, and its extension to DRIFT-II and DRIFT-III are envisaged. Recently another group, NEWAGE[54], has joined the development of TPCs for WIMP detection, with a micro-TPC where the readout is performed by a microdots structure.

The field of WIMP direct detection is going through a phase in which a great diversity of techniques are being developed and tested. This diversity is important, as it must clarify which techniques will prevail in the next generation of experiments. Currently the best exclusions are obtained by cryogenic hybrid detectors, whose success is based on a powerful separation between electron and nuclear recoils, keeping on a second plane the more conventional strategies based on radiopurity and shielding. But if the WIMP lies relatively far from the present sensitivity levels (say, more than 3 orders of magnitude, for example) an important scaling up from the present prototypes is required, which seems a bigger challenge for cryogenic detectors than, for instance, Xenon ones. At those larger exposures, neutron background will limit the sensitivity and again shielding techniques will become important in any case. The strategy of self-shielding, at reach for large, position sensitive detectors may well be the successful next step. In addition, in case a WIMP appears, as

an irreducible background, in these kind of detectors, strategies to positively identify it must be prepared. Any of the three signatures being pursued will be useful, and specially the directionality one.

3 Axions searches

Axion phenomenology[7,8] depends mainly on the scale of the PQ symmetry breaking, f_a. In fact, the axion mass is inversely proportional to f_a, as well as all axion couplings. The proportionality constants depend on particular details of the axion model considered and in general they can be even zero. An interesting exception is the coupling axion-photon, which arises in every axion model from the necessary Peccei-Quinn axion-gluon term. This interaction is phenomenologically described by:

$$L_{a\gamma\gamma} = -g_{a\gamma\gamma}\phi_a \mathbf{E}\cdot\mathbf{B} \tag{1}$$

where ϕ_a is the axions field, $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic fields, and $g_{a\gamma\gamma} = \alpha C_\gamma/\pi f_a$ the axion-photon coupling, being α the fine structure constant and C_γ is a model dependent constant, usually of order unity (for example, $C_\gamma \sim 0.97$ for the KSVZ[55,56] model and $C_\gamma \sim -0.36$ for the DFSZ[57,58] model).

The only axion phenomenology assumed in all experiments presented in the next paragraphs is this axion-photon coupling. This coupling allows for the conversion of axion into photons in the presence of (electro)magnetic fields, a process usually called Primakoff effect and that is beneath all the detection techniques described in the following.

3.1 Galactic axions

Axions could be produced at early stages of the Universe by the so-called misalignment (or realignment) effect[8]. Extra contributions to the relic density of non-relativistic axions might come from the decay of primordial topological defects (like axion strings or walls). There is not a consensus on how much these contributions account for, so the axion mass window which may give the right amount of primordial axion density (to solve the dark matter problem) spans from 10^{-6} eV to 10^{-3} eV. For higher masses, the axion production via these channels is normally too low to account for the missing mass, although its production via standard thermal process increases. Thermal production yields relativistic axions (hot dark matter) and is therefore less interesting from the point of view of solving the dark matter problem, but

in principle axion masses up to ~ 1 eV, are not in conflict with cosmological observations[59].

The best technique to search for low mass axions composing the galactic dark matter is the microwave cavity originally proposed in[60]. In a static background magnetic field, axions will decay into single photons via the Primakoff effect. The energy of the photons is equal to the rest mass of the axion with a small contribution from its kinetic energy, hence their frequency is given by $hf = m_a c^2(1 + O(10^{-6}))$. At the lower end of the axion mass window of interest, the frequency of the photons lies in the microwave regime. A high-Q resonant cavity, tuned to the axion mass serves as high sensitivity detector for the converted photons.

The Axion Dark Matter Experiment (ADMX)[61,62] has implemented the concept using a cylindrical cavity of 50 cm in diameter and 1 m long. The Q is approximately 2×10^5 and the resonant frequency (460 MHz when empty) can be changed by moving a combination of metal and dielectric rods. The cavity is permeated by a 8 T magnetic field to trigger the axion-photon conversion, produced by a superconducting NbTi solenoid.

So far the ADMX experiment has scanned a small axion mass energy, from 1.9 to 3.3 μeV[62] with a sensitivity enough to exclude a KSVZ axion, assuming that thermalized axions compose a major fraction of our galactic halo (ρ_a = 450 MeV/c^2). An independent, high-resolution search channel operates in parallel to explore the possibility of fine-structure in the axion signal[63]. The detailed exclusion is shown in fig. 2.

Current work focuses on the upgrade of the experimental set-up, which means basically to reduce the noise temperature of the amplification stage. This is being done by newly developed SQUID amplifiers and in a later stage by reducing the temperature of the cavity from the present 1.5 K down to below 100 mK by using a dilution refrigerator. These improvements will allow ADMX to increase the sensitivity to lower axion-photon coupling constants and also to larger axion masses.

3.2 Solar axions

Axions or other hypothetical axion-like particles with a two-photon interaction can also be produced in the interiors of stars by Primakoff conversion of the plasma photons. This axion emission would open new channels of stellar energy drain. Therefore, energy loss arguments constrain considerable axion properties in order not to be in conflict with our knowledge of solar physics or stellar evolution[69].

In particular, the Sun would offer the strongest source of axions being a

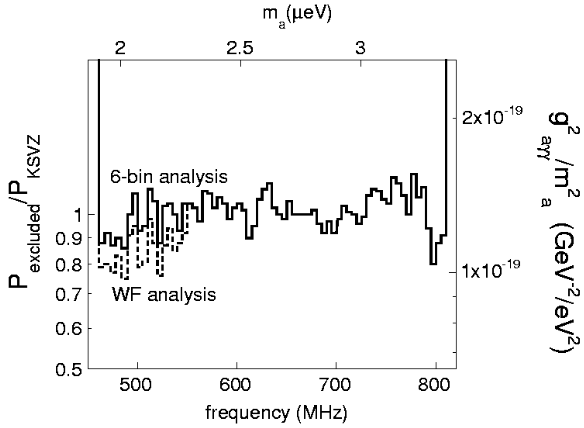

Figure 2. Upper limit on axion-to-photon conversion power and coupling $g_{a\gamma\gamma}$, excluded at greater than 90% confidence, assuming axion halo density 0.45 GeV/cm^3.

unique opportunity to actually detect these particles. The solar axion flux can be estimated [64,65] within the standard solar model. The expected number of solar axions at the Earth surface is $\Phi_a = (g_{a\gamma}/10^{-10}\,\mathrm{GeV}^{-1})^2\, 3.54 \times 10^{11}$ cm^{-2} s^{-1} (being $g_{a\gamma}$ the axion-photon coupling) and their energies follow a broad spectral distribution around $\sim$4 keV, determined by solar physics (Sun's core temperature). Solar axions, unlike galactic ones, are therefore relativistic particles.

These particles can be converted back into photons in a laboratory electromagnetic field. Crystalline detectors may provide such fields [66,72], giving rise to very characteristic Bragg patterns that have been looked for as byproducts of dark matter underground experiments [73,74,75]. However, the prospects of this technique have been proved to be rather limited [67], an do not compete with the experiments called "axion helioscopes" [68,64], which use magnets to trigger the axion conversion. This technique was first experimentally applied in [70] and later on by the Tokyo helioscope [71], which provided the first limit to solar axions which is "self-consistent", i.e, compatible with solar physics. Currently, the same basic concept is being used by the CAST collaboration at CERN [76,77] with some original additions that provide a considerable step forward in sensitivity to solar axions.

The CAST experiment is making use of a decommissioned LHC test mag-

net that provides a magnetic field of 9 Tesla along its two parallel pipes of 2×14.5 cm^2 area and 10 m long. These numbers mean that the axion-photon conversion probability is a factor 100 higher than in the previous best helioscope at Tokyo. The CAST magnet has been mounted on a platform that allows to point it to the Sun and track it during $\sim$3 h per day in average. The rest of the day is devoted to measure the background experimentally. CAST adds up expertise in low background techniques to operate three different X-ray detectors with complementary approaches: a TPC, a MICROMEGAS and a CCD. A relevant component of the experiment is the X-ray focussing mirror system, designed and built as a spare system for the X-ray astronomy mission ABRIXAS, and now recovered for CAST. It provides a focussing of the X-rays coming out of the magnet down to a spot of a few mm^2 on the CCD, further increasing the signal-to-noise ratio and therefore the sensitivity of the experiment.

CAST has been running in 2003 and, in improved conditions, in 2004. The results of the analysis of the 2003 data have been recently released[77]. No signal above background was observed, implying an upper limit to the axion-photon coupling $g_{a\gamma} < 1.16 \times 10^{-10}$ GeV^{-1} at 95% CL for the low mass (coherence) region $m_a \lesssim 0.02$ eV. As can be seen in figure 3 this limit is a factor 5 more restrictive than the limit from the Tokyo axion helioscope and already comparable to the one derived from stellar energy-loss arguments. The 2004 data will allow to improve the sensitivity of the experiment close to the expectation of the experiment proposal. Currently the experiment is being adapted for the second phase which consist in data taking with a buffer gas (He^4 and/or He^3) inside the magnet pipes. Varying the pressure of the gas allows to match the coherence condition for a range of higher axion masses up to $\sim$eV. As can be seen in figure 3, CAST phase II sensitivity will enter for the first time the region of the axion parameter space where the most theoretically motivated axion models lie.

3.3 Laboratory axions

The existence of axions or other axion-like particles may produce measurable effects in the laboratory. A typical example is the "light through wall" experiments, in which a photon beam is converted into axions inside a magnetic field and, after crossing an optical barrier, are converted back into photons by another magnetic field. As a result, light seems to have gone through an opaque wall. This technique was used to derive some early limits on the axion properties [78].

A more subtle effect is the magnetic-induced birefringence of the vacuum.

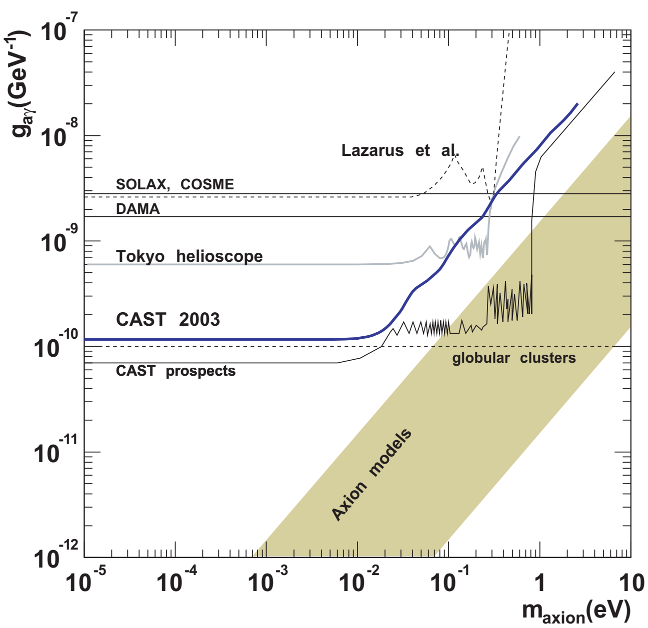

Figure 3. 95% CL exclusion line obtained from the analysis referred to in the present paper (line labeled "CAST 2003"), compared with other limits.

When a polarized photon beam traverses an empty space permeated with a magnetic field, the polarization component parallel to the magnetic field gets out-of-phase with respect the perpendicular one, producing an *ellipticity* on the final polarization of the beam. Such an effect is predicted by standard QED by virtue of four-legged fermion loops, although its magnitude is extremely small. Experiments with ultra-precise optical equipment may look for such an effect. The PVLAS experiment[79], designed to measure the QED-predicted magnetic-induced birefringence has been systematically detecting such a signal, however 4 orders of magnitude larger than expected. After several years of tests to rule-out possible systematic effects, the collaboration has officially announced that they are indeed detecting an unusually large unexplained ellipticity in their laser beam[79] connected with the presence of the magnetic field. One tentative explanation might be the presence of an photon-axion oscillation. Such scenario predicts a second effect which would distinguish it from the standard QED effect. It consists of a rotation of the polarization (or *dichroism*) due to the reduction of one the polarization com-

ponents, produced by real photon-axion conversion. The presence of such additional effect has been recently confirmed also by PVLAS. However, the interpretation of PVLAS observation in terms of axions needs an axion mass of ~ 1 meV and an axion-photon coupling of $\sim 10^{-6}$ GeV^{-1}, far larger than present experimental and solar limits[79] (although exotic extensions of the standard axion scenario may allow to reconcile all experimental results[80]). In any case, the nature of the PVLAS effect is still an open question.

4 Conclusions

A review of the current status of the experimental searches for WIMPs and axions has been given. The field lives a moment of great activity, triggered by the fact that very well motivated theoretical candidates could be within reach of present technologies. The presence of intriguing positive signals both in WIMPS and axion detection has at least enhanced the interest and excitation of the research. The next years will witness the results of many very interesting developments currently ongoing to define and operate a new generation of experiments, well into the region of interest for both WIMPs and axions.

5 Acknowledgements

I would like to dedicate the present review to the memory of prof. A. Morales. I am indebted to him for many years of collaboration and tutoring in the field of direct searches for dark matter. He used to give very detailed and thorough reviews on dark matter in the most important international conferences. His last review, in the TAUP2003 at Seattle[21] has been particularly useful in the WIMP section of the present review.

References

1. D. N. Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **148** (2003) 175 [arXiv:astro-ph/0302209].
2. J. R. Primack, D. Seckel and B. Sadoulet, Ann. Rev. Nucl. Part. Sci. **38** (1988) 751.
3. G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267** (1996) 195 [arXiv:hep-ph/9506380].
4. R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38** (1977) 1440.
5. S. Weinberg, Phys. Rev. Lett. **40** (1978) 223.
6. F. Wilczek, Phys. Rev. Lett. **40** (1978) 279.
7. G. G. Raffelt, Phys. Rept. **198** (1990) 1.

8. M. S. Turner, Phys. Rept. **197** (1990) 67.
9. J. Edsjo, Nucl. Phys. Proc. Suppl. **143** (2005) 435.
10. L. Bergstrom, Rept. Prog. Phys. **63** (2000) 793 [arXiv:hep-ph/0002126].
11. P. Belli, R. Cerulli, N. Fornengo and S. Scopel, Phys. Rev. D **66** (2002) 043503 [arXiv:hep-ph/0203242].
12. Phys. Rev. D **67** (2003) 103507 [arXiv:astro-ph/0208010].
13. A. M. Green, Phys. Rev. D **68** (2003) 023004 [Erratum-ibid. D **69** (2004) 109902] [arXiv:astro-ph/0304446].
14. J. D. Lewin and P. F. Smith, Astropart. Phys. **6** (1996) 87.
15. A. K. Drukier, K. Freese and D. N. Spergel, Phys. Rev. D **33** (1986) 3495.
16. S. Cebrian *et al.*, Astropart. Phys. **14** (2001) 339 [arXiv:hep-ph/9912394].
17. P. F. Smith and J. D. Lewin, Phys. Rept. **187** (1990) 203.
18. D. N. Spergel, Phys. Rev. D **37** (1988) 1353.
19. A. Morales, Nucl. Phys. Proc. Suppl. **110** (2002) 39 [arXiv:astro-ph/0112550].
20. A. Morales, Nucl. Phys. Proc. Suppl. **114** (2003) 39 [arXiv:astro-ph/0211446].
21. A. Morales, Nucl. Phys. Proc. Suppl. **138** (2005) 135.
22. A. Morales *et al.*, Phys. Lett. B **532** (2002) 8 [arXiv:hep-ex/0110061].
23. L. Baudis *et al.*, Phys. Rept. **307** (1998) 301.
24. H. Klapdor-Kleingrothaus [Heidelberg-Moscow and GENIUS Collaborations], Eur. Phys. J. C **33** (2004) S962.
25. S. Schonert *et al.* [GERDA Collaboration], Nucl. Phys. Proc. Suppl. **145** (2005) 242.
26. M. L. Sarsa *et al.*, Phys. Lett. B **386** (1996) 458.
27. R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1** (2003) 1 [arXiv:astro-ph/0307403].
28. R. Bernabei *et al.*, Nucl. Phys. Proc. Suppl. **138** (2005) 48.
29. S. Cebrian *et al.*, Nucl. Phys. Proc. Suppl. **138** (2005) 147.
30. J.W.Kwak *et al.*, to appear in the Proceedings of the Workshop for the Identification of Dark Matter (IDM04), Edinburgh, september 2004.
31. R. Bernabei *et al.*, Phys. Lett. B **436** (1998) 379.
32. R. Bernabei *et al.*, New J. Phys. **2** (2000) 15.
33. G. J. Alner *et al.* [UK Dark Matter Collaboration], Astropart. Phys. **23** (2005) 444.
34. E. Aprile *et al.*, New Astron. Rev. **49** (2005) 289.
35. S.Moriyama *et al.*, to appear in the Proceedings of the Workshop for the Identification of Dark Matter (IDM04), Edinburgh, september 2004.
36. R. Brunetti *et al.*, arXiv:astro-ph/0411491.
37. C. Arnaboldi *et al.* [CUORE Collaboration], Nucl. Instrum. Meth. A **518** (2004) 775 [arXiv:hep-ex/0212053].
38. C. Arnaboldi *et al.*, Phys. Lett. B **584** (2004) 260.
39. C. Arnaboldi *et al.* [CUORE Collaboration], Astropart. Phys. **20** (2003) 91 [arXiv:hep-ex/0302021].
40. D. S. Akerib *et al.* [CDMS Collaboration], Phys. Rev. Lett. **93** (2004) 211301 [arXiv:astro-ph/0405033].

41. V. Sanglard *et al.* [The EDELWEISS Collaboration], Phys. Rev. D **71** (2005) 122002 [arXiv:astro-ph/0503265].
42. J. H. Yoo, talk given at the workshop "The Dark Side of Universe", 22-26 May 2005, Seoul, Korea (http://newton.kias.re.kr/dm/).
43. S. Cebrian *et al.*, Phys. Lett. B **563** (2003) 48.
44. G. Angloher *et al.*, Astropart. Phys. **23** (2005) 325 [arXiv:astro-ph/0408006].
45. N. Coron, G. Dambier, E. Leblanc, J. Leblanc, P. de Marcillac and J. P. Moalic, Nucl. Instrum. Meth. A **520** (2004) 159.
46. S. Cebrian *et al.*, Astropart. Phys. **21** (2004) 23.
47. T. Girard *et al.*, arXiv:hep-ex/0505053.
48. M. Barnabe-Heider *et al.* [PICASSO Collaboration], arXiv:hep-ex/0502028.
49. C. Winkelmann *et al.*, arXiv:astro-ph/0504629.
50. I. Giomataris and J. D. Vergados, Phys. Atom. Nucl. **67** (2004) 1097 [Yad. Fiz. **67** (2004) 1125].
51. S. Aune *et al.*, arXiv:hep-ex/0503031.
52. R. Ayad *et al.*, Nucl. Phys. Proc. Suppl. **124** (2003) 225.
53. C. J. Martoff, D. P. Snowden-Ifft, T. Ohnuki, N. Spooner and M. Lehner, Nucl. Instrum. Meth. A **440** (2000) 355.
54. K. Miuchi *et al.*, to appear in the Proceedings of the Workshop for the Identification of Dark Matter (IDM04), Edinburgh, september 2004.
55. J. E. Kim, Phys. Rev. Lett. **43** (1979) 103.
56. M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Nucl. Phys. B **166** (1980) 493.
57. M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B **104** (1981) 199.
58. A. R. Zhitnitsky, Sov. J. Nucl. Phys. **31** (1980) 260 [Yad. Fiz. **31** (1980) 497].
59. S. Hannestad, A. Mirizzi and G. Raffelt, arXiv:hep-ph/0504059.
60. P. Sikivie, Phys. Rev. Lett. **51** (1983) 1415 [Erratum-ibid. **52** (1984) 695].
61. S. Asztalos *et al.*, Phys. Rev. D **64** (2001) 092003.
62. S. J. Asztalos *et al.*, Phys. Rev. D **69** (2004) 011101 [arXiv:astro-ph/0310042].
63. L. Duffy *et al.*, arXiv:astro-ph/0505237.
64. K. van Bibber, P. M. McIntyre, D. E. Morris and G. G. Raffelt, Phys. Rev. D **39** (1989) 2089.
65. R. J. Creswick, F. T. Avignone, H. A. Farach, J. I. Collar, A. O. Gattone, S. Nussinov and K. Zioutas, Phys. Lett. B **427** (1998) 235 [hep-ph/9708210].
66. E. A. Paschos and K. Zioutas, Phys. Lett. B **323** (1994) 367.
67. S. Cebrian *et al.*, Astropart. Phys. **10** (1999) 397 [arXiv:astro-ph/9811359].
68. P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983) Erratum ibid. **52**, 695 (1984).
69. G. G. Raffelt, Ann. Rev. Nucl. Part. Sci. **49**, 163 (1999) [hep-ph/9903472].
70. D. M. Lazarus, G. C. Smith, R. Cameron, A. C. Melissinos, G. Ruoso, Y. K. Semertzidis and F. A. Nezrick, Phys. Rev. Lett. **69** (1992) 2333.
71. S. Moriyama et al., Phys. Lett. B **434**, 147 (1998) [hep-ex/9805026].
72. R. J. Creswick, F. T. . Avignone, H. A. Farach, J. I. Collar, A. O. Gattone, S. Nussinov and K. Zioutas, Phys. Lett. B **427** (1998) 235

[arXiv:hep-ph/9708210].
73. F. T. . Avignone *et al.* [SOLAX Collaboration], Phys. Rev. Lett. **81** (1998) 5068 [arXiv:astro-ph/9708008].
74. A. Morales *et al.* [COSME Collaboration], Astropart. Phys. **16**, 325 (2002) [hep-ex/0101037].
75. R. Bernabei *et al.*, Phys. Lett. B **515** (2001) 6.
76. K. Zioutas *et al.*, Nucl. Instrum. Meth. A **425** (1999) 480 [arXiv:astro-ph/9801176].
77. K. Zioutas *et al.* [CAST Collaboration] Phys. Rev. Lett. **94** (2005) 121301 [arXiv:hep-ex/0411033].
78. S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592** (2004) 1.
79. G. Cantatore *et al.*, to appear in the Proceedings of the Workshop for the Identification of Dark Matter (IDM04), Edinburgh, september 2004.
80. E. Masso and J. Redondo, arXiv:hep-ph/0504202.